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FULL SCALE ICEBERG IMPACT: A PILOT EXPERIMENT IN ANTARCTICA

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ABSTRACT

A 1700 tonne iceberg was towed by a D8 bulldozer into a rock face in 13m water depth. The impact occurred at a velocity of 0.89 m/s and lasted 2.25 seconds. We estimate the impact force to be between 4.5 and 6.5 MN, the contact area between 1.8 and 3.6m^2 and the impact pressure between 1.3 and 3.6 MPa.

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INTRODUCTION

Fixed man-made structures have now extended into waters frequented by icebergs. One such structure is the runway under construction at Dumont d'Urville, Terre Adélie, Antarctica (Figs. 1,2). Another is the gravity-based structure (GBS) planned for the Hibernia oil field offshore Newfoundland. Indeed, iceberg collision dictates the shape of the Hibernia GBS.

So far, little is known about actual iceberg collisions. Most of the data available comes from small-scale laboratory experiments. The largest contact area reached so far was achieved at Pond Inlet by tunnelling into a grounded iceberg and pushing a medium-scale hemispherical indentor into the ice (Johnson and Benoit, 1987). Extrapolation of these results to actual collisions two or three orders of magnitude greater in contact area is problematic due to the scale effect of ice. Iceberg ramming experiments with instrumented icebreakers have also been proposed but not yet performed.

The idea of towing an iceberg into a cliff to study a full scale impact was first proposed by Ken Croasdale of Esso Resources, Canada. In 1983 the Hibernia partners actually started work on the project by performing precision iceberg towing trials and searching for suitable impact sites offshore Labrador.

In 1988 the idea was revived by C-CORE (Centre for Cold Ocean Resources Engineering) which performed model experiments to evaluate various towing methods and also proposed a test site near St. Anthony, Newfoundland (Duthinh, et al., 1989). C-CORE and EPF (Expeditions Polaires Françaises) also agreed to join forces in a pilot experiment to take place at Dumont d'Urville, to take advantage of several factors:

- an abundance of icebergs in the vicinity,
- the presence of steep rocky cliffs,
- the presence of towing machinery, such as bulldozers, and
- the existence of a runway which could allow the bulldozers to gain speed.

PILOT EXPERIMENT

The goal of the experiment was to test the methodology under actual field conditions, to gain experience, and if possible, to collect meaningful data. Since this was the first experiment of its kind, we decided to keep it simple and to use a very small iceberg.

Using a Zodiac and a small aluminium boat, we captured a 5,000 tonne iceberg which happened to drift close to the chosen site, which was a rock cliff that extended to a depth of 13 m below water at an angle of 45-60° from horizontal (Fig. 3). In front of the cliff we anchored a light net 20 m wide and 8 m deep equipped with insulation foam at the nodes (Photo 1); we hoped that damage to the foam would provide an estimate of the contact area; the foam also provided buoyancy to the net. The berg was held in place by a 120 m towing hawser looped around it and anchored to the cliff. Unfortunately, the berg soon broke into three pieces, with the largest one furthest from the cliff. We decided to use the largest piece, which meant we had to free the smaller ones first.

A steady current complicated things by keeping the bergs huddled together at the end of the loop of the taut hawser. We tied a small line to the ends of the hawser and to a D8 Caterpillar. To ensure that the collision would occur over the net, we passed the small line through a truck tire anchored above the target (Photo 2). Short, incremental pulls on the hawser caused the icebergs to drift toward the cliff. The hawser slackened enough to be slipped around the two smaller bergs, thus freeing them. We then boarded the remaining berg and deployed a motion sensor (Lever, et al., 1986, Photo 3).

For safety reasons, we decided to remove the smaller line. To cause slack on the line, the D8 travelled about 10m in first gear, but even this little pull nearly caused the iceberg to collide prematurely with the cliff. Luckily, the current soon pushed the berg back 40-50m, so the hawser was taut again. In our first attempt, the D8 pulled the berg to within 10-15 m and then stopped (Photo 4). Contrary to our expectations, however, the berg stopped short of the cliff, probably because of a switch in wind direction.

Our second attempt was successful; the bulldozer pulled the berg to within 5m of the cliff, then stopped and let it drift freely. There was a cracking sound coming from underwater. The berg yawed and pitched backwards slightly as its front rode up the cliff. Small chunks of ice (estimated to be 20-50 kg in size) floated up. Clumps of foam also broke free from the net and floated away (cover photo).

RESULTS

Figure 4 shows the linear accelerations, angular accelerations and angular velocities of the iceberg at about the moment of impact. The data was collected at 120 Hz and stored in the motion sensor itself, which had been triggered remotely. Due to the proximity of the South Magnetic Pole, the compass did not work and only five degrees of freedom were measured (i.e. the angle ϕ in Fig. A3 was set to zero for all times).

The coordinate system is right-handed orthogonal with z vertical, positive upward, x and y horizontal of arbitrary orientation, rotating with the berg. The rotations are positive clockwise looking out from the origin along the relevant axis. The neglect of ϕ and $\dot{\phi}$ affects all three rotations (but especially ω_z) and all three accelerations.

Figure 5 shows an idealized plan view of the iceberg above water shape as measured by a party which boarded the berg after the impact. The iceberg mass was estimated to be 1700 tonnes.

After the impact, a diver went down to examine the cliff and the net. He reported an elliptical hole in the net of principal axes 2m by 3m (area 4.7m^2) as well as lumps of foam encrusted in the cliff (Fig.6). The foam was attached to ridges in the cliff covering an area of 1.6m^2. The net was retrieved, laid flat on the ground and the area that had been either torn, or from which foam was missing, was measured and found to be 3.6m^2 (Fig. 7).

IMPACT VELOCITY

Shortly after the impact, the iceberg came to rest and the measured accelerations also went to zero (within noise). Integrating backwards over the impact duration (2.25 seconds) gave the velocity just prior to impact (there was a small error in this integration due to x and y changing direction during the impact).

$v_x = 0.83$ m/s $\quad v_y = 0.31$ m/s $\quad v_z = 0.22$ m/s

The resultant velocity was $v = 0.91$ m/s .
The horizontal velocity was $v_h = 0.89$ m/s (3.2 km/hr)

This result agreed with the bulldozer driver's observation: he was going as fast as first gear allowed, which was about 3.0 km/hr.

IMPACT FORCE AND PRESSURE

Table 1 shows the iceberg acceleration for various assumed locations of the centre of rotation (CR) of the iceberg (see Appendix). Fortunately, there was little rotation and the acceleration was not too sensitive to the location of the CR which is unspecified because the submerged shape was unknown. Assuming the berg CR to have been at $r' = (0,0,+5)$ metres (r' is defined in the Appendix) the peak deceleration during the impact was 2.16 m/s^2, corresponding to a maximum impact force of:

$$F = 1.5 \times 1.7 \times 10^6 \text{kg} \times 2.16 \text{ m/s}^2 = 5.51 \times 10^6 \text{N}$$

and a maximum global pressure of

$$p = \frac{5.51 \times 10^6 \text{N}}{1.8 \text{m}^2} = 3.1 \times 10^6 \text{Pa}.$$

In the above calculations, a hydrodynamic added mass coefficient of 1.5 has been assumed.

Coordinates of r' (metres)			Accelerations (m/sec^2)			
x	y	z	a_x	a_y	a_z	Resultant
0	0	+5	-1.56	-1.22	0.85	2.16
0	+2	+5	-1.56	-1.22	0.85	2.16
0	-2	+5	-1.56	-1.22	0.85	2.16
+2	0	+5	-1.54	-1.16	0.70	2.05
-2	0	+5	-1.57	-1.27	1.01	2.26
0	0	+4	-1.70	-1.21	0.85	2.25
0	0	+6	-1.41	-1.22	0.85	2.05

Table 1 Iceberg Acceleration at Impact (m/s^2) as a Function of Location of Centre of Rotation

ERROR ANALYSIS

We think that the estimation of the iceberg mass from the linear dimensions is accurate to within 25%. We also think that the iceberg centre of rotation is very likely within the box [±2, ±2, ±1] described in Table 1. This shows the resultant acceleration to be accurate within 10%. Therefore, the relative error on impact force is estimated to be 35%. The maximum impact force is in the interval:

$$5.51 \text{ MN}\left[1 - \frac{0.35}{2}, 1 + \frac{0.35}{2}\right] = [4.5, 6.5] \text{ MN}.$$

In the calculation of pressure, the largest error comes from the estimation of contact area. We estimate the actual contact area to be within the interval [1.8, 3.6m^2] because: 1) not all the foam clumps involved in the collision remained attached to the rock face and therefore 1.8m^2 was a lower bound and 2) the torn area of the net was likely greater than the area directly caught between the iceberg and the cliff. The maximum global impact pressure is therefore in the interval:

$$\left[\frac{4.5}{3.6}, \frac{6.5}{1.8}\right] = [1.3, 3.6] \text{ MPa}.$$

FUTURE WORK

Clearly, for the contact area achieved here, more accurate methods exist than towing an iceberg into a cliff, (e.g. a medium-scale indentor could be used, as in Pond Inlet). This pilot experiment, however, can be extended to collect data on larger collisions by instrumenting a small or medium iceberg. Towing from land works well: two bulldozers could be used in tandem to tow a medium iceberg. Guidance to the target could also be resolved by simple means, provided the current was not too strong.

The measurement of contact area is the greatest source of errors. Possibilities worth investigating include smoothing the surface of the cliff (or using a wharf), covering it with clumps of fast setting hydraulic cement at discrete intervals, etc... Ultimately, the cliff could be instrumented with pressure panels.

To locate the centre of rotation more accurately, two motion sensors may be used (see Appendix), thus rendering the accurate determination of underwater shape unnecessary. If little rotation occurs during the impact, the impact force is not very sensitive to the location of the centre of rotation and observation of draft and underwater shape by a diver should suffice.

To improve their chances of success, future experimenters should have a supply boat at their disposal to actively search for and tow suitable icebergs rather than limit themselves to those bergs that happen to drift close to the site. A helicopter would also be most useful in deploying instrumentation and taking stereo photography of the iceberg, thus eliminating the need to board the iceberg.

The added mass of the iceberg at collision needs to be investigated. One simple scheme consists in measuring the towing force at various

towing speeds:

Constant Speed Test: $$F = F_D = \tfrac{1}{2}\rho C_D A v^2 \quad (1)$$

Open-water Variable Speed Test: $$F = F_D + F_I = \tfrac{1}{2}\rho C_D A v^2 + (m+m_{ao})\frac{dv}{dt} \quad (2)$$

Drift into cliff: $$0 = F_D + F_I = \tfrac{1}{2}\rho C_D A v^2 + (m+m_a)\frac{dv}{dt} + \frac{dm_a}{dt} v \quad (3)$$

where:

F	-	total force
F_D	-	drag force
F_I	-	inertial force
C_D	-	drag coefficient, assumed constant
A	-	underwater area normal to velocity
m	-	actual berg mass
m_{ao}	-	berg added mass in open water
m_a	-	berg added mass near cliff
v	-	berg velocity
ρ	-	berg density

By measuring F, v and ρ we obtain C_DA from (1).

By measuring F and v(t) we obtain m_{ao} from (2) with m inferred from aerial stereo photography of the emerged shape.

By measuring v(t) we obtain dm_a/dt with an initial m_{ao} at the moment of release. m_a is then updated and (3) gives $m_a(t)$. The underwater shape would serve to characterize m_a and solve for C_D. In the above method, wave making has been neglected. (In this experiment, we did not observe much of a bow wave). Also, any current in the immediate vicinity of the cliff has been ignored. For an account of wave-generation during iceberg acceleration, the reader is referred to Isaacson and McTaggart (1989).

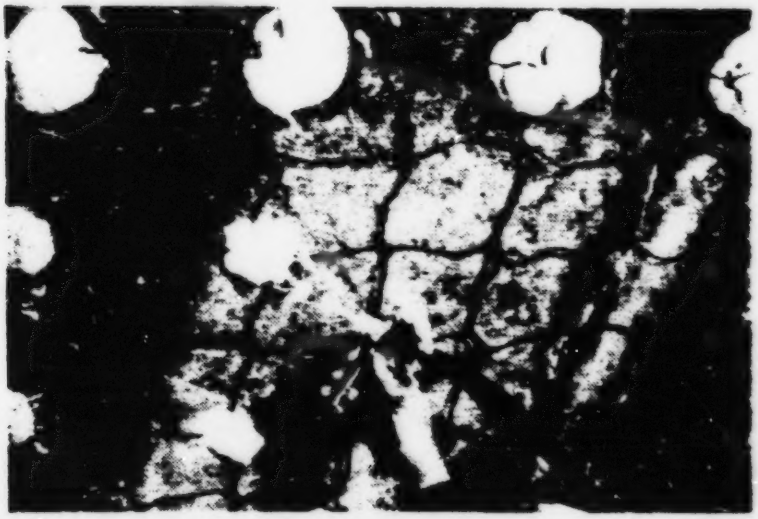

Photo 1 Fabricating the Contact Area Net

APPENDIX

Let x,y,z be the coordinates of a fixed cartesian frame attached to earth E and let x',y',z' be the coordinates of a moving cartesian frame attached to the centre of rotation G (Fig. A1). The acceleration of a particle S (i.e. the motion sensor) in the fixed frame is (all vectors except ω are in bold):

$$\mathbf{a} = \frac{\delta^2 \mathbf{r}'}{\delta t^2} + 2\boldsymbol{\omega} \times \frac{\delta \mathbf{r}'}{\delta t} + \frac{\delta \boldsymbol{\omega}}{\delta t} \times \mathbf{r}' + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}') + \frac{d^2 \mathbf{b}}{dt^2} \qquad (A1)$$

where $$\frac{\delta \mathbf{r}'}{\delta t} = \frac{dx'}{dt}\,\mathbf{i}' + \frac{dy'}{dt}\,\mathbf{j}' + \frac{dz'}{dt}\,\mathbf{k}' \qquad (A2)$$

and $$\frac{\delta^2 \mathbf{r}'}{\delta t^2} = \frac{d^2x'}{dt^2}\,\mathbf{i}' + \frac{d^2y'}{dt^2}\,\mathbf{j}' + \frac{d^2z'}{dt^2}\,\mathbf{k}' \qquad (A3)$$

are the velocity and acceleration of the particle as viewed by an observer in the moving frame. For a rigid body like an iceberg

$$\frac{\delta \mathbf{r}'}{\delta t} = \frac{\delta^2 \mathbf{r}'}{\delta t^2} = 0 \qquad (A4)$$

and $$\mathbf{a} = \frac{\delta \boldsymbol{\omega}}{\delta t} \times \mathbf{r}' + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}') + \frac{d^2 \mathbf{b}}{dt^2} \qquad (A5)$$

The motion sensor package measures $\mathbf{a}$ and $\boldsymbol{\omega}$ with respect to an inertial frame defined by local vertical, magnetic South and the right hand rule. Equation A5 allows the calculation of the acceleration of the centre of rotation $\frac{d^2 \mathbf{b}}{dt^2}$ for a given $\mathbf{r}'$.

Since $\mathbf{r}'$ (i.e. the location of the centre of rotation) is actually unknown, one may use a second motion sensor which gives:

$$\mathbf{a}_2 = \frac{\delta \boldsymbol{\omega}}{\delta t} \times \mathbf{r}'_2 + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}'_2) + \frac{d^2 \mathbf{b}}{dt^2} \qquad (A6)$$

From Eqs. (A5), (A6) and the distance $\mathbf{r}'-\mathbf{r}'_2$ one can determine $\frac{d^2 \mathbf{b}}{dt^2}$, $\mathbf{r}'$ and $\mathbf{r}'_2$.

Normally (x',y',z') is obtained from (x,y,z) by three successive rotations (around z, N and z') over the Euler "astronomical" angles (Fig. A2).

Krilov (Blagoveshchensky, 1962) noticed that the Euler angles can attain large values for small motions (the reader can convince herself by trying y = y' and z' in the xz plane, a small angle away from z) and proposed a new set of rotations called the Euler-Krilov "nautical" angles (Fig. A3). First is a rotation of angle ϕ about z, then a rotation of angle θ about the nodal line N, and finally a rotation of angle ψ about y'. The three rotation matrices are:

$$D = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \quad B = \begin{bmatrix} \cos\psi & 0 & -\sin\psi \\ 0 & 1 & 0 \\ \sin\psi & 0 & \cos\psi \end{bmatrix}$$

The Euler-Krilov transformation is:

$x' = Ax$ with $A=BCD$

Photo 2 Iceberg Collision Guidance System

Photo 3 Deploying the Motion Sensor

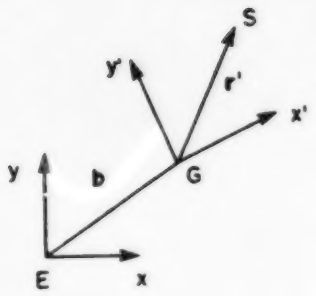

Fig. A1 Coordinates

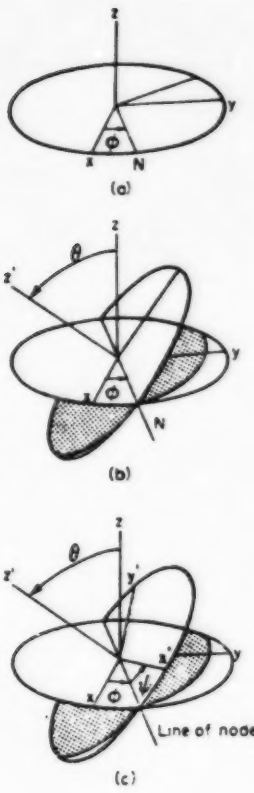

Fig. A2 Euler Angles

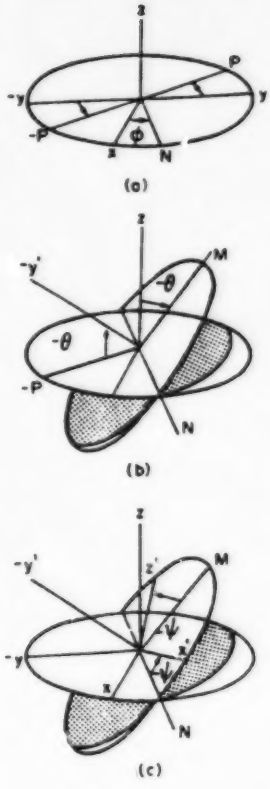

Fig. A3 Euler-Krilov Angles

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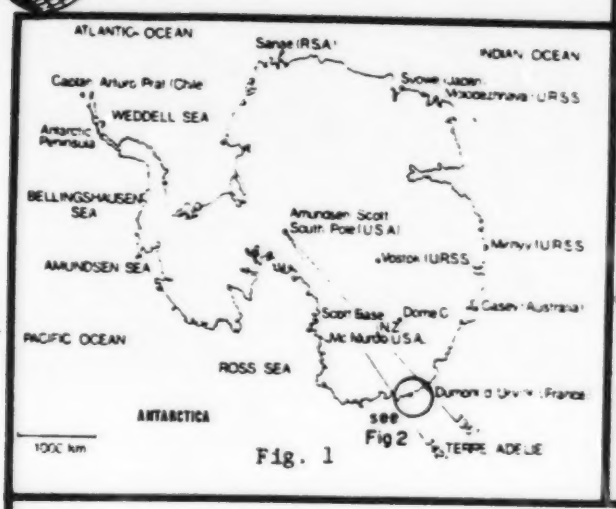

Fig. 1

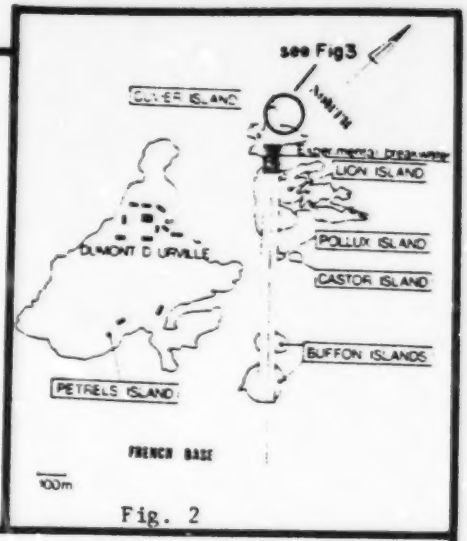

Fig. 2

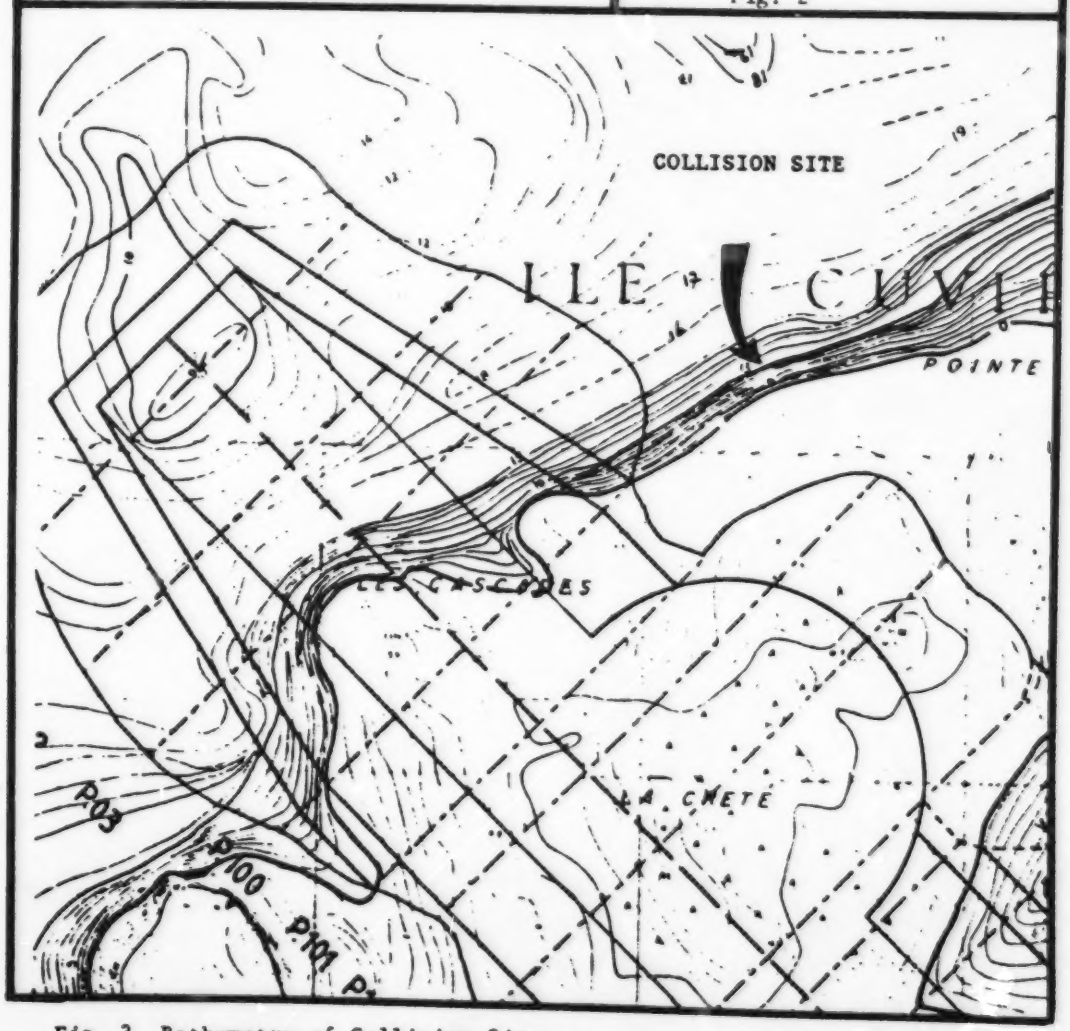

Fig. 3 Bathymetry of Collision Site.

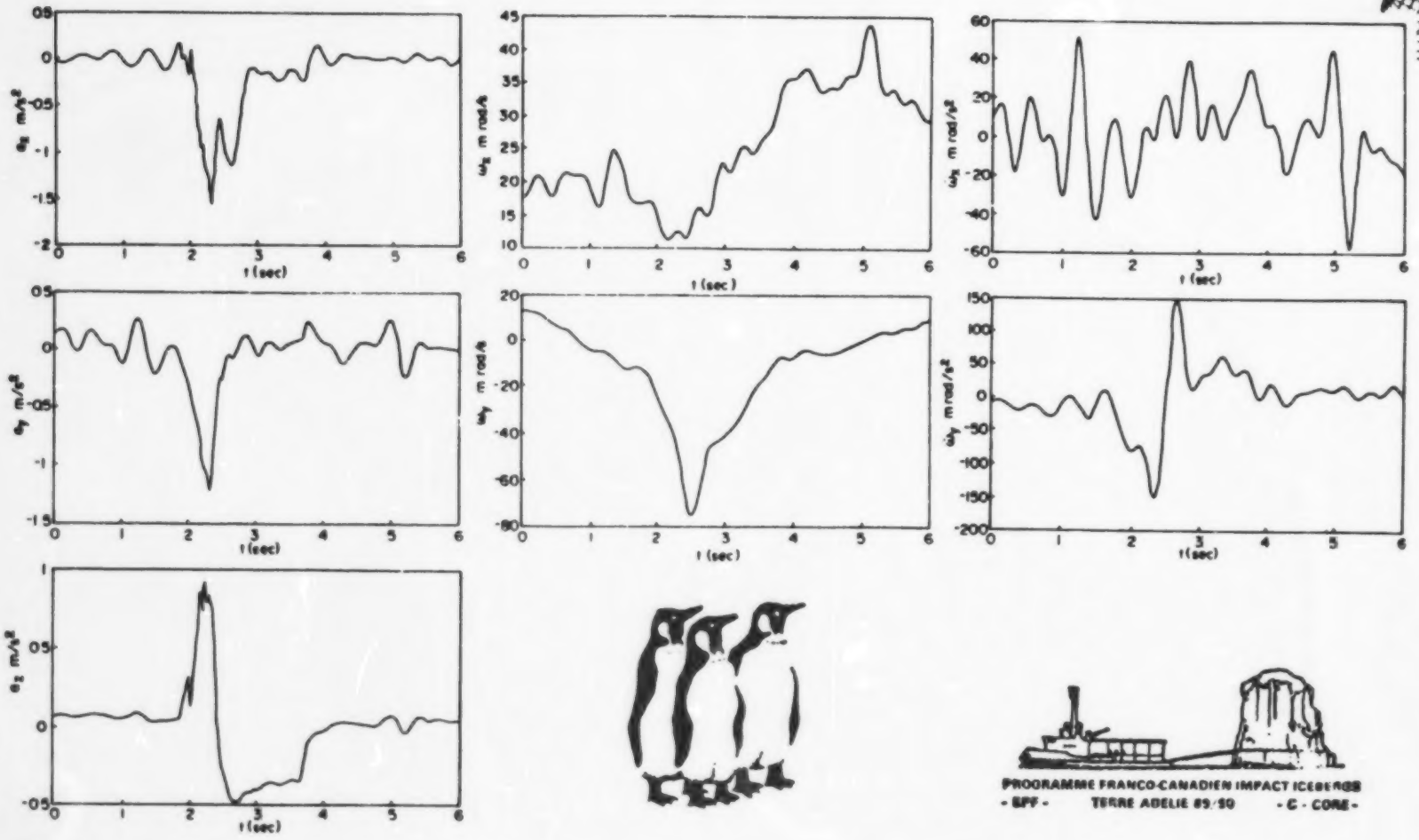

Fig. 4 Linear Accelerations, Angular Velocities and Accelerations at Impact.

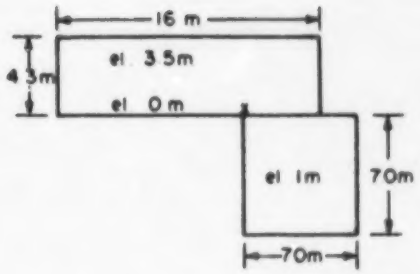

Fig. 5 Schematic of Berg Emerged Shape. x Shows Location of Motion Sensor

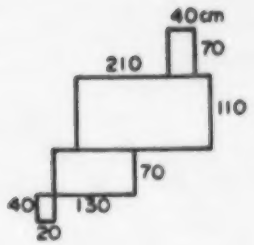

Fig. 7 Area of Net Either Torn or With Foam Missing

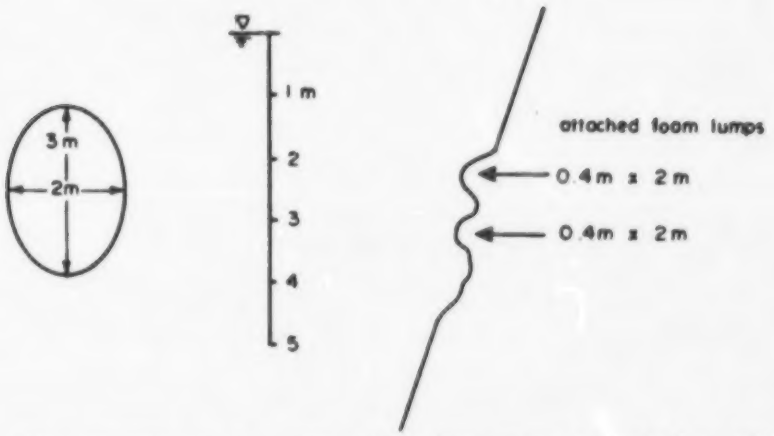

Fig. 6 Hole in Net and Ridges With Foam Attached as Observed by a Diver After the Collision

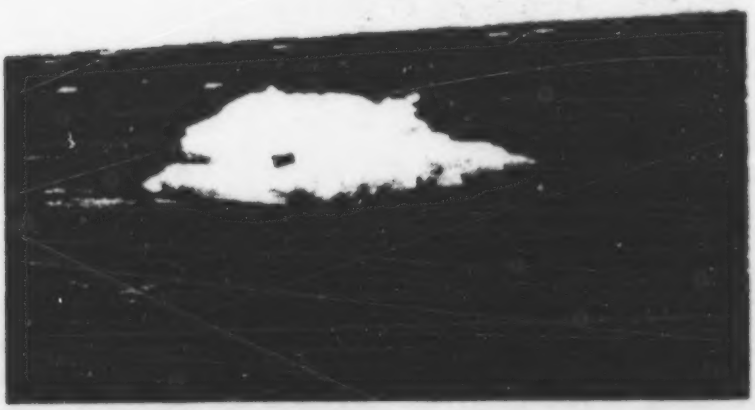

Photo 4 Towing the Instrumented Iceberg